Test Program for Enhancing Blast Capacity of Windows

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Abstract

Personnel injury from flying glass produced during an explosion accident can represent a significant hazard, often in excess of hazards due to airblast, primary fragments, building collapse, and secondary fragments. The permissible overpressure in Inhabited Building Distance (IBD) from a Potential Explosion Site (PES) is 1.2 psi. This pressure is sufficient to cause failure of most windows in conventional construction. Failure of these windows can produce hazardous glass shards which can cause serious injury.

A research program was initiated to address this issue and develop cost effective methods for mitigating the hazards. The program was designed to address blast loads with a peak pressure up to 7 psi. Anchored widow film systems were designed and tested for low pressure applications. These methods showed a significant increase in blast capacity and reduction in glass fragment hazard. A catch system was developed to arrest the flight of unanchored, filmed panes for blast loads at the upper end of the design range. An analytical method was developed for these capacity enhancement systems. Over 60 validation tests were performed to verify the analytical methods. These tests included evaluation of polyester films, tear resistant films, and laminated glass. Tests were performed in a shock tube capable of producing long duration blast loads with accurate control over peak pressure.

Introduction

Terrorist activities involving explosives have the potential to produce a number of hazards to building occupants ranging from flying debris to structural collapse. While media attention of recent incidents has seemingly focused on the more spectacular damage such as collapse of building facades, the most common hazard is flying glass. A case in point is the Oklahoma City tragedy which resulted in the loss of 168 lives, most of which were caused by failure of the structural system; however, the number of people injured by flying glass was over 300 which accounted for the majority of injuries outside the collapse zone. This situation is typical for explosion incidents, whether they are terrorist bombs or vapor cloud explosions at petrochemical plants.

Glass Hazards

Glass presents a significant hazard in these situations for a number of reasons. First, the glass used in most conventionally constructed buildings is quite weak with respect to the rest of the structure. Glass fibers are very strong; however, glass panes are weak because their strength is limited by

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random flaws within the pane. This prevents glass from achieving significant tensile stresses to resist blast loads without failing. Other materials which can deform plastically, such as steel, are able to absorb some or all of the blast loading and fail in a controlled, ductile manner. Glass on the other hand, fails in a brittle manner and under high pressure loads, produces high speed shard fragments which have the potential to cause serious injury. The geometry of these pieces is such that edge-on fragments have a very small presented area, therefore, the velocity required to penetrate vital organs is fairly low compared to other types of construction debris.

Another factor which makes glass a troublesome hazard is that it covers large portions of the exterior of buildings and thus can affect a very large number of people. Since most of the windows in conventional construction can only resist a peak dynamic load typically less than 0.5 psi, the distance from an explosion in which glass fails is typically quite large. For example, a 1,000 lb bomb could produce reflected pressures sufficient to fail windows out to a distance of 1,300 ft. Weak windows may fail at even lower pressures, thus the zone of glass failure is extended beyond this distance.

Window hazards also exist for refineries and petrochemical facilities which have the potential for vapor cloud explosions, pressure vessel bursts, and other explosion hazards. These sites typically have control rooms which are designed to resist blast loads produced by an accidental explosion. However, they also have a large number of administration buildings, maintenance shops, and other facilities which have been designed for conventional loads only and have low blast resistance. Typically these structures have large glass areas, many of which face the process units, and present significant glass hazards to personnel. Some petrochemical companies have recognized the potential hazard of glass in support buildings and have developed programs and criteria to address and mitigate the hazard.

Protection Criteria

In Department of Defense (DoD) criteria (Reference 1), the maximum permissible side-on (free-field) overpressure at buildings which do not support the operations at a Potential Explosion Site (PES) is 1.2 psi. The distance at which the peak blast pressures have dropped to this level is termed Inhabited Building Distance (IBD). Structural damage to conventional buildings will occur at this overpressure level; however, DoD has accepted the risks associated with this damage. This overpressure level of 1.2 psi is sufficient to cause failure in most windows of conventionally constructed buildings. This means that buildings located at IBD from a PES may sustain significant glass damage including the formation of hazardous glass shards.

A key decision to be made when evaluating window hazards and developing mitigation methods is whether to *eliminate* or to *reduce* the hazard. This decision can significantly impact the cost of upgrades because elimination of hazards can be much more expensive than reduction only. Hazard *reduction* measures might include relocation of personnel to reduce exposure or application of safety film to reduce the projection of glass shards. Other measures might involve changes in security procedures and addition of security devices. Hazard *elimination* methods include elimination of the window or replacement of windows panes with laminated glass or polycarbonate. These measures are typically more expensive than the hazard reduction methods and they are not feasible if the building frame cannot survive the increased load applied by glass which remains in the frame.

Ultimately the criteria for protection must be made on permissible risk and available funds. In federal buildings as well as industrial facilities, protection criteria has not been well defined at this point. As a result, facility managers have a difficult time determining the best approach to addressing potential hazards.

Research Program

Wilfred Baker Engineering, Inc., (WBE) established the Technology Cooperative in 1993 which is a joint industry program to address safety issues related to explosion hazards at refineries and petrochemical plants. The focus of the first two program years of this Cooperative was development of methods to mitigate glass hazards in conventional buildings. Companies participating in the initial Technology Cooperative program were Exxon, Union Carbide, Phillips, and Texaco. These were joined in the second program year by Hoechst-Celanese, DuPont, and Shell.

WBE developed a multi-phase program to develop mitigation methods for glass hazards. The blast load range of interest for the program was a peak pressure less than 7 psi with a duration of approximately 35 ms. This load was selected as an upper bound for the blast capacities of administration and support buildings although load durations may be much longer. Cooperative participants determined that the majority of buildings which would require window upgrades were subjected to blast loads at or below this level. At higher blast loads, buildings containing windows would not be able to survive and thus there was not a benefit to upgrading the blast capacity of the windows beyond the capacity of these structures.

Material Type

The program was designed to develop methods for existing windows of which the vast majority is annealed glass. This is the weakest of the commonly available glazing materials with tensile strengths typically ranging down to 4,000 - 5,000 psi. These low tensile strengths are caused by flaws in the glass panes which cause failure of the pane well below the strength of individual glass fibers. Strength of windows can also be influenced by handling of the glass during installation as well as aging due to environmental conditions. This means that glass typically becomes weaker over its useful life.

Another type of commonly used glass in commercial facilities is tempered. The tensile strength of tempered glass is increased in manufacturing by heating of the glass pane followed by rapid cooling which produces residual compressive stresses in the outer sections of the glass pane when it cools. This pre-stressing increases the flexural strength of the glass making it much stronger than annealed. Tempering also affects the breakup pattern under high blast loads. Tempered glass breaks up into small, cubic type fragments as opposed to the shard like fragments from annealed glass. The striking velocity of tempered glass fragments must be much greater than for annealed glass fragments to cause organ penetration and substantial risk of fatalities. While this will not reduce the number of people impacted by the glass fragments, it will clearly reduce the overall hazard.

Upgrade Levels

Mitigation methods were segregated into two classes of upgrades, Level I and Level II. Level I methods were designed for blast loads ranging up to 4 psi with durations of approximately 35 ms. Frames for conventional windows were expected to remain attached to the structural frame at this load level, thus making it possible to develop methods which utilize the strength of the existing frame to eliminate the glass hazard. Level II upgrades addressed blast overpressures ranging from 4 - 7 psi with durations in the range of 30 ms. Existing frames are typically not adequate to resist these loads and thus must be replaced or reinforced.

Technical Approach

The overall approach for the entire program development was to develop an engineering method for designing specific components based on the applied load and performing a limited number of tests to validate the engineering method. This approach permits use of the methodologies over a range of window sizes and blast loads. In many cases, tests were used to determine allowable ductility ratios (amount of plastic response) to be used in theoretical development of the engineering methods.

Level I

Mitigation methods developed for Level I were classified as minor upgrades. This means that substantial modifications to the building structure are not required to accomplish these mitigation measures. The two primary mitigation measures developed for Level I were installation of polyester safety film and sub-dividing window frames to reduce the span of existing glass.

Reduced Span

Since resistance of a member responding in flexure is dependent on the span or distance between supports, the addition of division bars or mullions across the window to reduce the glass span intuitively has the ability to increase the blast capacity of existing windows. In some cases, this method can increase the blast capacity of the windows by 50%. This methodology was not tested in this program because response can be reliably (conservatively) predicted with standard engineering mechanics.

Safety Film

Unanchored

The second method for mitigating blast loads for Level I is the application of safety film to the window pane. A primary function of safety film is to bond the glass shard fragments together to significantly diminish the penetrating hazard of unmitigated window glass. The film in this situation does not increase the strength of the glass at all, it simply holds the glass fragments together. This changes the hazard from one of penetrating glass shards to a blunt trauma hazard produced by a filmed piece of glass. In addition to changing the hazard, this type of mitigation measure also significantly reduces the number of people affected by failure of the windows. In this application, film

is applied up to the limits of the glazing bead or gasket around the window. This is commonly referred to as a “daylight” application. This method was addressed as an alternative in the design guide prepared for this program and was tested under a later program.

Anchored

A second use for safety film is in an anchored application. This involves applying safety film to the glass and attaching it to the frame in such a way that when the glass breaks, the film acts as a catch for the fragments. In this application, the film is responding in membrane action and does not produce composite action with the glass pane to increase the strength.

Two anchored film application methods were evaluated for this program. The first was a “battened” system in which film is applied to the window with an additional length, or tail, of film that is turned 90° and secured to the window frame with an aluminum bar. Screws are used to attach the battened bars to the frame as shown in Figure 1. The battens are typically placed on two sides, causing the film to respond in one-way action.

A second anchored film method is called “wet glaze.” In this method, the existing glazing gaskets around the windows pane are removed and safety film is applied to the edges of the glass, extending into the glazing well or bite. A structural silicone adhesive is then applied into the glazing well as shown in Figure 2. This adhesive anchors the film and glass to the window frame. It also provides a relatively soft support which serves to absorb some of the blast energy applied to the window. As with the battened system, the strength of the glass does not increase and the film simply serves to trap the glass fragments.

Film Considerations

The film normally used for these applications is a high strength polyester with a yield strength of approximately of 15,000 psi. A significant disadvantage to polyester film is that it is notch sensitive and tends to fail catastrophically once a tear occurs. For this reason, it is necessary to provide adequate factors of safety on ductility when using film as a mitigation method.

A significant advantage of the battened film system is that it does not require removal of the glass and is relatively inexpensive. It can provide a significant increase in the capacity over untreated annealed glass and can virtually eliminate the glass hazard. Disadvantages include difficulty in installation of the film especially for thicknesses greater than 10 mil. Weathering can also weaken the film and reduce its effectiveness. The typical life span for good quality safety film is approximately 10 years. Care is required for installation which should be accomplished by an experienced installer of safety film. Another disadvantage of battened film systems is “leakage” of a small number of glass fragments around the film on the non-anchored sides.

A wet glaze system offers the similar advantages and disadvantages as the battened system. However it does produce a less obtrusive installation and provides substantially greater ductility than the battened system. Another significant advantage is the ability of the wet glaze to absorb blast energy and reduce the net tension in the film. A significant disadvantage is that some frames may not be

suitable for installation of the adhesive, primarily because it is not possible to remove the existing glazing material.

A new type of film which is classified as tear resistant was also evaluated. Under static loads, this film does not exhibit the catastrophic tearing evident in normal polyester films. It appears to delaminate and tear in separate directions to achieve this type of action. During dynamic tests, it showed some increase in ductility over standard film but it still exhibited sudden tearing failures under blast loads. A significant consideration however, for this material is the increased cost. This material does have a higher yield strength than most polyester films; thus, it can provide a greater strength for the same thickness of film.

Level II

Level II methods are classified as major upgrades. This is because they require substantial work to the window frame and/or other portions of the structure. These methods include replacement of the existing window with laminated glass and installation of a catch system. Laminated glass is constructed by attaching two pieces of glass together with a poly vinyl butryl (PVB) interlayer. A typical thickness for the interlayer is 60 mil (0.060 inch). This product responds quite well under blast loads primarily because it is able to achieve relatively large deflections after the glass plys break due to the presence of the interlayer. This interlayer holds the glass fragments together following cracking due to the applied blast load.

To develop the full strength of the laminated glass, it is necessary to provide a deep bite or rebate in the glazing well. A small bite will allow the laminated glass pane to slip through the framing. This produces perhaps the greatest difficulty in installing laminated glass in existing buildings. Many buildings do not have frames that are capable of supporting the laminated glass. This is unfortunate because laminated glass certainly provides an excellent means for providing windows with a substantial blast capacity.

An alternate type of system developed for Level II was a catch system composed of horizontal venetian blind slats supported by steel cables attached to the structural frame of the building. Polyester safety film is applied to the inside face of the glass to hold the fragments together. This filmed piece of glass strikes the catch system producing significant deformation in the slats and cables. During this response, a significant amount of blast energy is absorbed. The catch system provides the capability to significantly restrict the range of the debris and essentially eliminate the hazard to building occupants.

A similar catch system concept is used in Europe which utilizes a flexible curtain over the window called a Bomb Blast Net Curtain (BBNC). Additional length of curtain is placed in a box below the window to provide additional mass and drag as the filmed glass is pushed out of the frame.

Testing

The engineering guideline developed during the program included pressure-impulse (P-i) diagrams which could be used to select the proper film thickness based on span, material strength, and anchorage method. A total of 25 tests were run to validate the film selection methodology developed for the engineering guideline as outlined in Table 1. A total of 62 tests were performed during the project.

All tests performed in support of the window hazard mitigation program were conducted in a 3 ft diameter shock tube developed by WBE. This tube utilizes a driver of compressed air and an aluminum burst diaphragm. An example of a blast load produced by the shock tube is shown in Figure 3. Test windows were mounted in a steel fixture secured to the end of the shock tube. Blast pressure gauges were placed in the end plate above and to the side of the test windows. Gauges were PCB piezoelectric type with one microsecond digitization of the signals.

Table 1. Test Matrix

No. of Tests	Test	Materials	Window Size (in)	Range of Pressures (psi)
11	Plain glass	Annealed 3/16" 1/4"	15, 21	1.5 - 6.5
16	Battened film	Polyester film 4, 12 mil	15, 21	2 - 6.5
9	Wet glazed film	Polyester film 4, 12 mil structural silicone adhesive	15, 21	2 - 10
4	Tear resistant film	Polyester film (3 m) 4, 8 mil	15	1 - 2.5
4	Laminated glass	1/8 x 1/8 30, 60 mil interlayer wet glaze	15	6 - 10
18	Catch system	Aluminum, E-glass slats 1.8, 3/16" cable	15, 21	2.5-10

Two additional shock tubes, one 3 ft square and the other 8 ft square, have also been developed and are currently in use to test a variety of construction materials including reinforced concrete, concrete masonry units, blast doors, and windows.

Level I

A total of 16 tests were performed on battened systems with window sizes ranging from 15 to 21 inches. These tests utilized 4 mil (0.004 inch) and 12 mil (0.012 inch) film with a yield strength of 16 ksi. The blast load for each test was selected from the engineering guideline equal to the test

article's predicted capacity. The test item was inspected to evaluate adequacy of response. Filmed test specimens were marked with an ink grid prior to testing. Following each test, the grid dimensions were measured to determine permanent strain in the film. This information was used to evaluate the effective ductility of the film during dynamic response.

As expected, the 12 mil film performed much better than 4 mil film. It showed a higher resistance to tearing than did the 4 mil and retained a higher percentage of glass fragments. For cases in which the film remained anchored to the frame, a small dusting of glass was produced at the top and bottom of the pane. This resulted from the ejection of glass fragments inside the glazing well at the edges of the pane. These fragments were not well trapped by the film and thus were not restrained completely in the frame. The percentage of glass fragments ejected from the filmed specimens was less than 5%. Peak blast capacity of 4 mil film developed during the testing was approximately 3 psi. Twelve mil film was able to resist loads up to 6.5 psi for a 15 inch square window. This was well in excess of the failure pressure of untreated annealed glass which was approximately 2.5 psi.
Eight tests were performed for wet glazed systems to validate the engineering procedure. These tests showed no failure of 4 mil film at up to 3.8 psi and up to 9.8 psi for 12 mil film. In general, the wet glaze film provided approximately 50% greater capacity than the battened film. This is primarily due to the soft support provided by the structural silicone adhesive which reduced the effective load applied to the film.

Level II

A limited number of tests were performed on laminated glass to determine the relative conservatism of existing design guidelines. Test specimens were composed of two panes of 1/8 inch annealed glass with 30 mil (0.030 inch) and 60 mil (0.060 inch) PVB interlayers. These windows were able to achieve blast capacities between 6.5 and 11 psi with a duration of approximately 35 ms.

An analytical method was developed to predict the blast capacity of the venetian blind system with cable (wire rope) supports. The system responds essentially as a partially loaded catenary which produces a complex numerical solution. A total of 9 tests were performed on the catch systems with safety film applied to the non-blast face of all specimens and to the blast face of a limited number of test items. Window sizes were 21 inch square with 3/16 inch annealed glass. Aluminum and E-glass slats were evaluated during testing. The maximum deflection of the catch system under the peak load of 7 psi was approximately 13 inches. Fragment retention on the filmed glass was approximately 95%.

Conclusions

The program for developing methods of mitigating blast hazards for glass has produced a number of approaches for enhancing the blast capacity of windows. This work has application for a variety of conventionally constructed buildings subjected to blast pressures up to approximately 7 psi. This work was sponsored by a consortium of petrochemical companies with an urgent need for addressing glass hazards at their facilities due to potential explosions.

The technical approach for development of the mitigation methods consisted of developing engineering procedures which were then validated by tests under blast load conditions. A shock tube developed by WBE was used to produce the blast load environment. This tube provided an excellent means for producing consistent pressure-time histories which are representative of medium duration vapor cloud explosions.

Two levels of upgrade options were developed to provide economical solutions for various blast load levels. The Level I upgrades, which were effective up to approximately 4 psi, included span reduction, unanchored safety film and anchored safety film. Level II upgrades were designed for blast loads of 4 to 7 psi, and consisted of wet glazed laminated glass and a venetian blind catch system. Upgrades for blast loads beyond 7 psi, 35 ms were not pursued since they were beyond the blast capacity of conventional buildings.

References

1. "DoD Ammunition and Explosives Safety Standards," Department of Defense, DoD 6055.9-STD, October 1992

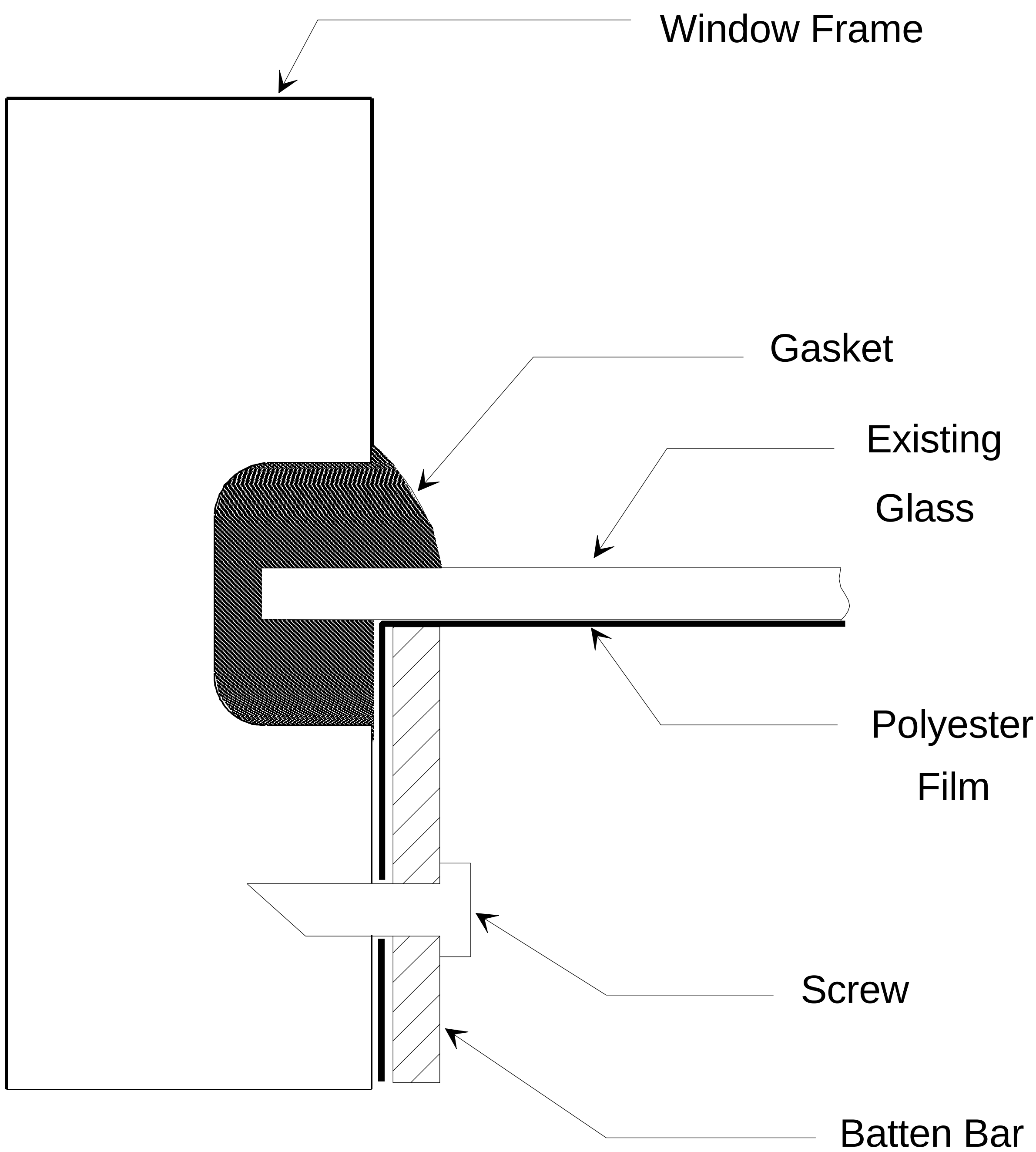

Figure 1. Anchored Film - Battened System

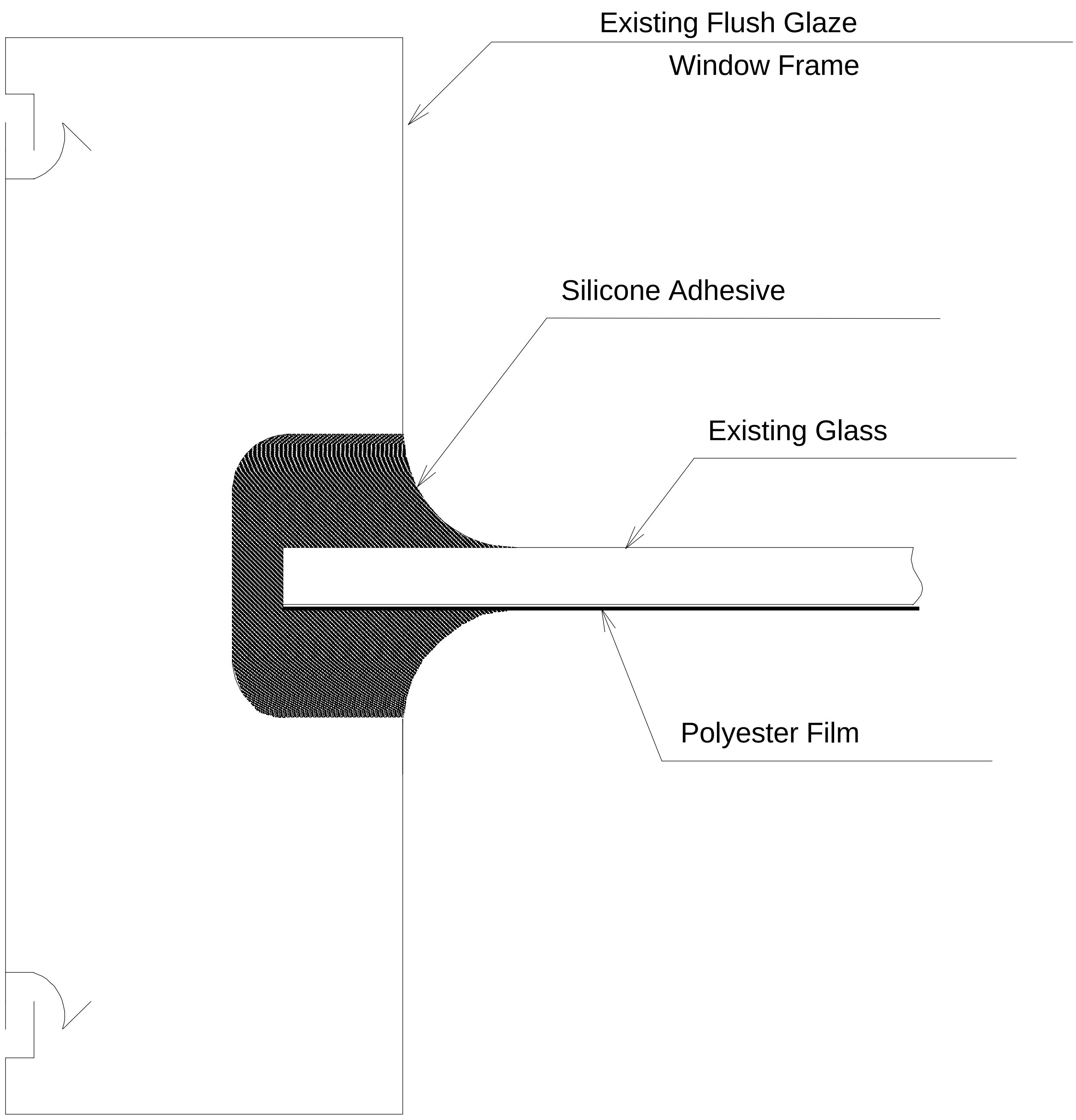

Figure 2. Anchored Film - Wet Glaze